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Nonlinear Processes in Geophysics

On aspects of the measurement of non-linear turbulence processes using the cluster wave experiments

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Abstract. The ESA/NASA Cluster mission has four identical satellites and is due for launch at the end of 1995. It will provide a unique opportunity to study medium scale processes in the region from inside the magnetopause to the solar wind. The polar orbit will allow measurements in the cusp and along auroral field lines, both regions where turbulence is to be expected. Five of the eleven instruments on each payload form the Wave Experiment Consortium (WEC); EFW, STAFF, WHISPER, WBD and DWP. The WEC is capable of a wide variety of wave and turbulence measurements. This paper outlines these capabilities and describes the form of the data which will be collected.

The paper gives a discussion of how the WEC data may be analysed so as to give an insight into the non-linear processes which occur in these regions of the space plasmas. There are many ways in which a plasma may be considered to behave in a non-linear manner. We concentrate on how the spatio-temporal turbulence in the plasma may be investigated so as to yield the energy spectrum with respect to both the frequency and wavenumber.

1 Introduction

In this paper we review the requirements for multi-spacecraft measurements to study processes in space plasmas (section 2). This provides a basis to discuss the measurements which will be available from the Cluster spacecraft (section 3). In section 4 we describe some specific studies which are planned for using the Cluster data and highlight the data handling methodology which may be used.

2 Multi-spacecraft measurements

With a single spacecraft one makes, usually locally, measurements along some world-line as is shown in figure 1(a). We do not, in general, have data in a plasma rest frame, $\mathbf{R_0}(x,y,z)$, but in some arbitrary spacecraft frame, $\mathbf{R}(x,y,z)$. Thus we need some technique to convert into the plasma frame of reference. An additional problem comes from the measurement process, we do not have a continuous function of $(\mathbf{R},t)$ along the world-line but instead we have discretized data as shown in figure 1(b).
In this discretization process we introduce aliasing which is a phenomenon which is explained in the frequency domain. Aliasing in the time domain produces frequency domain ambiguities. In the general space of figure 1 we get frequency and spatial ambiguities which may be thought of as the uncertainties in temporal and spatial variations which are inherent in single point measurements.

The data which we obtain from single point measurements can often be interpreted but this interpretation involves the assumption of some model of the phenomenon being studied. Examples of such models might be that we assume that the phenomenon is a spatial structure which is moving with the solar wind, or that we have some geometry to a structure such as that of a flux transfer event, FTE (Russell et al., 1978). The FTE example shows how this problem can be quite severe - the same, or similar, phenomenon is interpreted by Sibeck et al., (1989) as the temporal response of the magnetosphere to a pressure pulse in the solar wind. Others (for example, Lemaire et al., 1978) consider impulsive penetration to be the explanation of the observations. Many such examples of model dependent interpretation exist in the literature and frequently the authors do not state clearly their assumed (or, in some cases, biased) model as clearly as those cited here.

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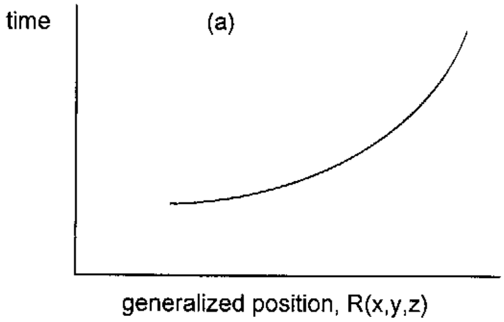

Fig. 1(a). Measurements of the space plasma are made along some world line.

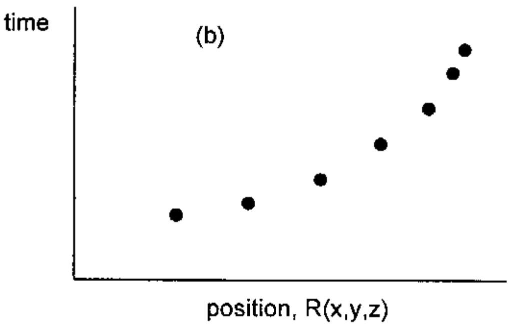

Fig. 1(b). The data are discrete samples of the parameter being measured.

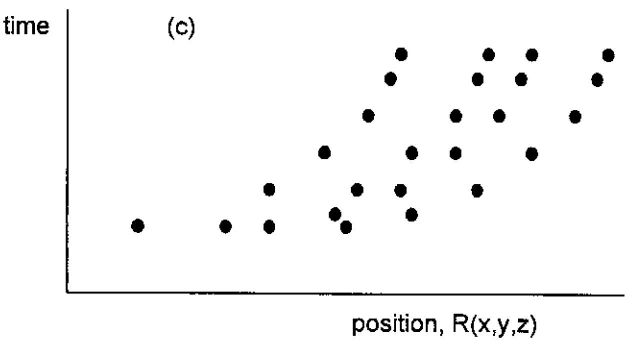

Fig. 1(c). With Cluster four sets of data will be available.

There has been much work done (e.g. Balikhin et al 1992; Pincon 1992) on the problem of converting from the frame **R** to $\mathbf{R_0}$. With the four Cluster spacecraft we will have something which can be sketched as in figure 1(c), i.e. four sets of discretized data along four worldlines. To understand the data, then, one needs to discuss the discretization (or data sampling), the timing and the worldlines (or orbit and spacecraft separation) for the Cluster mission.

Clearly this discussion has not mentioned what the measurements are which will be taken. The Cluster instruments will measure particles, electrons, low and high energy ions, fields and waves. These latter measurements are made by the Wave Experiment Consortium, WEC, and it is these measurements which will be the main consideration of what follows.

3 The Cluster Wave Experiment Consortium measurements

3.1 The Wave Experiment Consortium, WEC, was formed to optimise the use of the limited spacecraft resources of mass, power, data and booms (Lefeuvre et al., 1993). The WEC includes five experiments (Woolliscroft et al., 1993; Cornilleau-Werhlin et al; 1993, Gustafsson et al., 1993; Gurnett et al., 1993; Decreau et al., 1993) each led by a Principal Investigator as shown in table 1. This table also shows, in a highly abridged form, the key observational parameters of the five experiments. The Digital Wave Processor, DWP (Woolliscroft et al.., 1993; Woolliscroft et al., 1988), in addition to having scientific functions, is responsible for the control of the WEC and for providing the interface to the onboard data handling system for the WEC experiments (although the Wideband Plasma Wave investigation has an additional direct interface for use with the NASA DSN ground stations). Figure 2 shows the frequency range covered by the WEC instruments. A simplified block diagram of the WEC is given in figure 3.

The detailed choice of mode for each of the WEC instruments is quite complicated and will depend on, for example, the availability of DSN and whether the spacecraft data handling system is being operated in a high data rate. The choice of data rate is selected (within many constraints) by the Science Working Team so as to make the most effective use of the on-board data recorders. The data system does not have the capacity to handle all of the data per orbit.

DWP provides the control, some data processing and data handling for the WEC as well as having a particle correlator which takes data from the PEACE electron instrument (Johnstone et al., 1993). Macro command sequences will normally correspond to the WEC modes and are described more fully in (Dunford et al., 1992).

In order to have a reasonably consistent set of data throughout the mission the number of WEC modes has been restricted, although others can be uplinked.

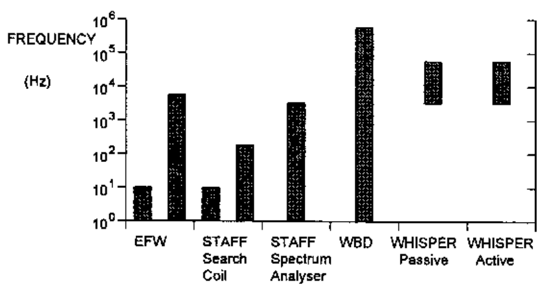

Fig. 2. A simplified view of the frequencies (in Hz) measured by the Cluster Wave Experiment Consortium, WEC. It should be noted that not all are simultaneously possible.

Table 1. The Wave Experiment Consortium (WEC) - summary capabilities.

Instrument	Principal Investigator	Key measurements
EFW	Gustafsson, G.	Two axis E (50 m wire booms) each sphere can work in current (Langmuir) or voltage mode, waveform up to 10 or 180 Hz (or higher with internal memory)
STAFF	Cornilleau-Wehrlin, N.	B tri-axial search coils, $f < 4$ kHz, waveform up to 10 or 180 Hz, auto- and cross- spectrum 3 B and 2 E components for $f < 4$ kHz
WHISPER	Décréau, P.M.E.	Relaxation sounder to determine n_e , total electric field power measurements in frequency 2 to 80 kHz, 300 Hz to 1 kHz resolution, Δt 13 ms to 0.8 s.
WBD	Gurnett, D.A.	Wideband measurements, E or B, 25 Hz to 9.5 kHz, 50 Hz to 19 kHz, or 1 kHz to 77 kHz output filters after frequency conversion with 0, 125, 250 or 500 kHz
DWP	Woolliscroft, L.J.C.	Particle correlator and data compression

There is more required to optimise the use of the WEC instruments. For example the EFW spherical probes have a bias current applied. This will be set up on a regular basis and it is not a parameter which needs to be adjusted for normal studies.

3.2 A further requirement for a high time resolution study of waves concerns the timing of the data. The acquisition of Cluster data by the onboard data handling system are normally timed with an accuracy of ± 2 ms. with respect to UTC for each spacecraft. To compare data from two spacecraft there is, then, an accuracy of $\pm$ 4 ms. Within DWP the timing is done more accurately and time differences may be measured to a few tens of microseconds (Dunford et al., 1992). The WBD data, when transmitted directly to the DSN ground stations, are timed at the ground to a higher accuracy and so radio interferometry based on the multi-spacecraft data will be possible. At lower frequencies DWP will enable plasma wave interferometry.

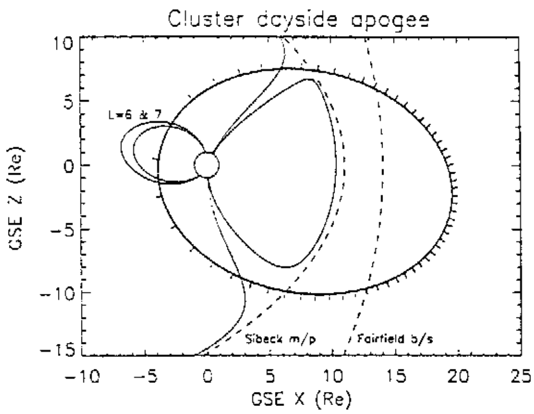

Fig. 4(a). Cluster dayside orbit (apogee noon local time) showing crossings of the cusp region. The tick marks on the orbit represent approximately the distance travelled in a two hour period. Some representative field lines (and the typical positions) of the main dayside boundaries are shown in thinner (and dashed) lines.

3.3 The orbits of the Cluster satellites are such that the interspacecraft separation will vary from a few hundred kilometres to a few thousand kilometres. Figure 4 shows the near polar orbit for when the spacecraft apogee is in the solar wind (apogee at noon local time) and in the magnetotail (apogee at midnight LT) respectively. These periods are six months apart with the spacecraft exploring the dawn and dusk flanks in-between. The mission duration is planned for at least two years (depending mainly on the use of fuel and the life of the equipment). Table 2 shows the planned typical interspacecraft separations during the different mission phases (but clearly these figures apply to the main scientific target point on the particular orbit).

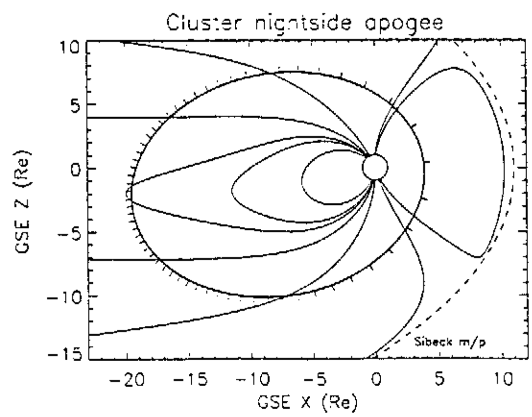

Fig. 4(b). As figure 4(a) but showing the orbit when apogee is in the magnetotail (midnight local time).

For the study of non-linear and turbulent processes we may summarise the main capabilities of the WEC in a single table as is given in the highly simplified Table 3.

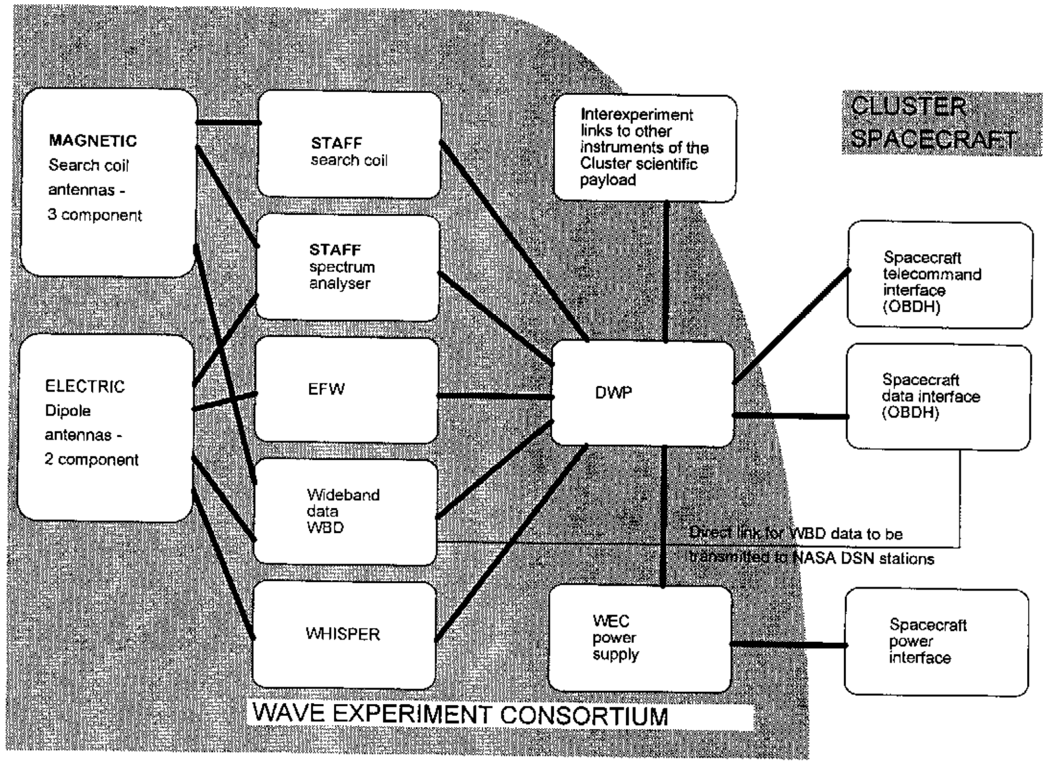

Fig. 3. A simplified block diagram of Cluster WEC showing only the main links between units with DWP (Woolliscroft et al., 1993; Woolliscroft et al., 1988) at the centre. OBDH interfaces (on-board data handling) are replicated for redundancy. STAFF (Cornilleau-Werhline et al., 1993), EFW (Gustafsson et al., 1993), WBD (Gurnett et al., 1993) and WHISPER (Decreau et al., 1993) are the other instruments in the WEC. This diagram shows the magnetic antennas of STAFF which are connected to the signal processing of EFW and WBD as well as STAFF and the EFW antennas which are connected to STAFF and WBD as well as being used for resonance sounding by WHISPER.

Table 2. Planned interspacecraft separation through the mission.

Year	Apogee in	Characteristic Separation	Comments
Year 1	Dayside (Cusp)	600 km (+/- 20%)	(characteristic separation applies to limited part of each orbit)
	Tail	2000 to 5000 km	(as above)
Year 2	Dayside (Cusp)	200 to 2000 km	decide after first cusp experience
	Tail	1 to 3 Earth radii	decide when fuel is known

4 Data Analysis Techniques

The CLUSTER mission provides an unprecedented opportunity to study spatial properties of different plasma parameters. Thus it is not surprising that a large effort is put on the development of spatio-temporal analysis techniques. As has already been highlighted, the concurrent use of different techniques is crucial for properly understanding turbulence and wave phenomena.

4.1 Spatio temporal properties

Many basic properties of spatio-temporal fluctuations can be investigated by means of well-known methods which are based on first or second order moments of the data. Best known are the correlation and power spectral techniques (Ritz et al., 1988). Such techniques have already been successfully applied to multipoint data by Russell (1988). Of particular importance are the separation of temporal from spatial scales (see, for example Escoubet, 1993) and the determination of the wave-vector distribution (Pincon, 1992).

These analysis techniques can be extremely powerful, and are appropriate for describing the linear properties of the plasma. However, they generally do not reveal the actual cause of the observed phenomena. The investigation of nonlinear phenomena, which are ubiquitous in plasmas, generally requires more advanced analysis techniques which depart from the more familiar second order moments. Pincon and Lefeuvre (1991) used second order statistics to determine the turbulent energy distribution in a simulated plasma without linear assumptions.

The field of linear data analysis is for obvious reasons the one to which so far most efforts have been devoted. Compared to it, the field of nonlinear data analysis looks much more like a heterogeneous and growing collection of different methods that are based on very different concepts. For that reasons, it is essential to know a priori what particular nonlinear process one is interested in, so that the most appropriate tool(s) can be used.

Table 3. A very simplified review of the main parameters of the Cluster WEC for the detailed analysis of non-linear processes.

Part(s) of WEC (etc)	Capability	Value	Constraints and notes
EFW and STAFF	Waveform sampling	f<10Hz (180Hz)	5 component 16 bit resolution, available most of the time. High bit rate value in brackets
EFW	Waveform (into memory)	f<32kHz	2 electric components (only short periods)
WBD	Waveform		in selected frequency bands
WHISPER	Spectrum	f between 4 and 80 kHz	many modes
WHISPER	Electron number density	1-100cm	from resonance sounding
EFW	Electron density fluctuations	f<4kHz	operation of each EFW probe can be in either current (n_e) or voltage (E) mode
DSN timing for WBD	Timing of WBD data for interferometry measuremnts using two or more spacecraft		Likely to be rather seldom available
DWP timing	On a single spacecraft, normal WEC relative timing.	±50 µs	Depends on processor load
Interspacecraft relative timing	±2 ms on each spacecraft	±4 ms	For comparison between the four spacecraft
Interspacecraft distance		±10km or 1%	whichever is greater

4.2 Nonlinear wave-wave interactions

The most straightforward approach to nonlinear analysis is based on a generalisation from second order spectra to higher order ones. Such polyspectral techniques have gained wide acceptance because they can easily be interpreted in terms of wave-wave interactions. The third and fourth order moments, called auto-bispectrum and auto-trispectrum, quantify the amount of phase coherence between respectively three and four waves. They are respectively estimated using the auto-bispectrum and auto-trispectrum where the auto-bispectrum is

$$B_f(f_1,f_2) = \langle X(f_1)X(f_2)X^*(f_1+f_2)\rangle \qquad (1)$$

where X(f) is the Fourier transform of the signal x(t) and brackets, $\langle\ \rangle$, denote ensemble-averaging and the auto-trispectrum can similarly be defined Both techniques have already been successfully applied to space plasmas (Lagoutte et al., 1989; Kravtchenko-Berejnoi et al., 1995; Dudok du Wit et al., 1995) and are appropriate for analysing strong plasma turbulence and identifying instability mechanisms (Krasnosel'skikh and Lefeuvre, 1992).

Although polyspectra have so far almost uniquely been applied to single time series (hence the prefix auto), they can be generalised to multipoint data. A combination of linear, quadratic and cubic interactions may give the more physical modelling (Krasnosel'skikh and Lefeuvre, 1992) A true polyspectrum in fact should not only involve frequencies, but wave-vectors as well. Quantities such as the true bicoherence

$$B_{f,\vec{k}}\left(f_1,f_2,\vec{k}_1,\vec{k}_2\right) = \left\langle X\left(f=f_1+f_2,\vec{k}=\vec{k}_1+\vec{k}_2\right) X^*\left(f_1,\vec{k}_1\right)X^*\left(f_2,\vec{k}_2\right)\right\rangle \qquad (2)$$

unfortunately cannot be accessed with Cluster because of the lack of spatial resolution. One may however consider cross-polyspectra, which are part of a more general, nonlinear and spatio-temporal description of the fluctuating field. Indeed, a simple way of describing a series of two-point measurements with linear and quadratic interactions, consists in writing (Ritz et al., 1988)

$$Y(f) = L(f)X(f) + \frac{1}{2} \sum_{\substack{f_1,f_2 \\ f=f_1+f_2}} Q_f(f_1,f_2)X(f_1)X(f_2) \quad (3)$$

where Y(f) and X(f) are the Fourier transforns obtained at two spatial locations, L(f) represents the linear transfer function and $Q_f(f_1,f_2)$ the quadratic one. The former describes the spatio-temporal dynamics of the fluctuations (dispersion, linear growth rate etc.) while the latter quantifies the wave-wave couplings and the energy transfers. Both quantities provide a wealth of information on the wavefield properties; their repetitive application to different spacecraft pairs allows the spatial dependence of the different quantities to be accessed.

4.3 Non Euclidean geometry and chaotic behaviour

Plasma turbulence often show a departure from Euclidean geometry. The appropriate concept for describing such properties is fractal dimension, which leads us to the field of chaotic system analysis. Although the idea of self-similar turbulence has been known for several decades, few applications to space plasmas have been reported and considerable progress still needs to be made in the comparative study of different regions.

Again, the analysis of single time series analysis has received much attention while that of spatio-temporal systems is still at its beginnings (Abarbanel et al., 1992). For this reason, only few truly multivariate techniques are available for analysing spatio-temporal data from Cluster.

It is well known that fully developed plasma turbulence often exhibits self-affine properties, that is, within a large range the different scales are self-similar. Since the seminal paper of Kolmogorov (Hunt et al., 1991), much work has been done to infer geometrical properties of the turbulence from structure functions. The latter is defined as

$$S(\Delta x, p) = \left\langle \left| v(x+\Delta x) - v(x) \right|^2 \right\rangle \quad (4)$$

where v(x) is generally the flow velocity. The analysis of solar wind turbulence (Burlaga, 1991; Marsch et al., 1994) has given evidence for spatial intermittency and for multifractality. The latter suggests that the underlying dynamical system should be low-dimensional. Such good results are corroborated by estimates of the correlation dimension (Wernik et al., 1994), which also yield low values of the dimension, but in other regions. Cluster should enable these analyses to be improved. First of all, it offers the possibility to select waves which have a given direction of propagation (using the wave-telescope method (Glassmeier et al., 1995)) and as such should allow the study of possible anisotropies in the fractal properties of the turbulence. Secondly, and more importantly, it allows testing of the hypothesis of frozen-in turbulence, which is often used as a hypothesis to replace v(x) by v(t) in the structure function.

4.4 Coherent structures

Regimes of fully developed plasma turbulence often exhibit self-organization which appears as large-scale and long-lived coherent vortices. Cluster is well suited for the study of such events, for which a spatio-temporal representation is crucial. Here again, several techniques that have been developed in other fields should be appropriate for Cluster. The conditional average technique (Johnson et al., 1987) and the biorthogonal decomposition (Dudok de Wit et al., 1994) both allow coherent structures to be identified and extracted on the basis of spatio-temporal data. By simultaneously analysing different plasma parameters, one can then determine the fraction of energy or particle flux which is associated with such structures; this in turn should greatly help their identification.

4.5 Other properties

The above mentioned techniques should already enable one to obtain a fairly complete picture of the basic properties of the turbulence. The list, however, is far from complete, and the field of spatio-temporal (or multivariate) analysis is still rapidly expanding. We just mention here information theoretic criteria for determining energy flows in wavenumber space (Ikeda et al., 1989) and soliton transforms for analysing solitary-like structures (Hada et al., 1993). Much progress can still be made in the analysis of spatio-temporal structures, for which there is no unique approach. There is no doubt that techniques such as the wavelet transform, with its good time-frequency localization properties (see, for example, Farge, 1992) will stimulate new developments.

The apparent redundancy between all these different approaches may at first appear as a disadvantage. Such a complementarity, however, is essential for properly describing the observed phenomena, while minimizing the bias that inevitably comes in through the choice of the analysis technique.

5 Conclusions

A full understanding requires full knowledge over all R,t space. This is clearly not possible. For any particular phenomenon an adequate set of information is restricted in R,t but care must be used because of ambiguities. The normal consideration of frequency aliasing is inadequate.

The applicability of these different techniques obviously varies with the kind of data that will be considered and with the time resolution of the different instruments. The wideband data of WBD are particularly appropriate for studying high frequency wave phenomena, such as nonlinear interactions between Langmuir waves. For some detailed studies of the frequencies observed the high frequency resolution of WHISPER over a wide frequency range will be of value. The discontinous operation mode of WBD, however, prevents large ranges of time-scales from being investigated. For that reason, techniques such as the structure function are not fully applicable.

The time-series of the STAFF and EFW instruments are more relevant for the analysis of low-frequency phenomena, such as nonlinear magnetic structures, whistler waves etc. These have synchronized (on one spacecraft) measurements of the wavefield at frequencies up to 180 Hz in high bit rate and 10 Hz in normal bit rate modes. The data from the magnetometer, FGM, overlap with STAFF at low frequencies. Techniques such as that discussed by Pincon et al., (1992) in principle allow the spatio-temporal properties of the wavefield to be inferred from 3 components of the magnetic field and the 2 components of the electric field.

A fuller analysis of the wavefield properties (such as the separation of different types of waves) will eventually require electron density data from WHISPER or other instruments on the spacecraft.

This short paper has not, for example, mentioned the study of turbulence by use of correlations in the DWP particle correlator (which takes a pulse train from the PEACE electron experiment). These measurements should provide evidence of the involvement of electrons in non-linear processes.

With Cluster we will have data which are good, even with a single spacecraft. With four spacecraft we get improvements in solving spatio-temporal ambiguities. But the analysis is still quite difficult and the goal of being able to avoid model dependent analysis is not possible.

Acknowledgements. The Cluster programme has had good support from ESA, NASA, the industrial teams and the national funding agencies. The work of many in the scientific community is acknowledged, especially the WEC chairs (present and past), the other WEC Principal Investigators and the WEC technical teams.

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